

Light-Emitting Diodes

3rd edition

E. Fred Schubert
Rensselaer Polytechnic Institute
Troy, New York, USA

ISBN: 978-0-9 863826-6-6

Publisher: E. Fred Schubert

Year: 2018

© E. Fred Schubert, all rights reserved

Light-Emitting Diodes

3rd edition

E. Fred Schubert

Rensselaer Polytechnic Institute

Troy, New York, USA

The 1st edition of the book “Light-Emitting Diodes” was published in 2003. The 2nd edition was published in 2006. The current 3rd edition of the book is a substantial expansion of the second edition and has 37 chapters. The book includes a thorough discussion of white light-emitting diodes (LEDs), phosphor materials used in white LEDs, packaging technology, and the various efficiencies and efficacies encountered in the context of LEDs. The background of light, color science, and human vision is provided as well. The fully colored illustrations of the 3rd edition are undoubtedly beneficial given the prominent role of light and color in the field of LEDs. The book is a comprehensive discussion of the LED, particularly its semiconductor physics, electrical, optical, material science, thermal, mechanical, and chemical foundations. The 3rd edition is published in electronic format in order to make the book affordable and easily accessible to a wide readership.

Table of contents

1	History of SiC light-emitting diodes	1-1
1.1	Silicon carbide (SiC)	1-1
1.2	Henry Round's demonstration of the first LED	1-2
1.3	Oleg Lossev's research on SiC LEDs	1-4
1.4	Kurt Lehovec's explanation of electroluminescence from p-n junctions	1-8
1.5	Post 1950s developments in SiC LEDs	1-9
1.6	LED centennial in 2007	1-9
	References	1-10
2	History of III–V light-emitting diodes	2-1
2.1	Compound semiconductors	2-1
2.2	The first III-V compound semiconductor LED	2-3
2.3	History of GaAs _y P _{1-y} alloy semiconductors and LEDs	2-5
2.4	History of GaAs and AlGaAs infrared and red LEDs	2-9
2.5	History of GaP and GaAsP LEDs doped with optically active impurities	2-12
2.6	History of AlGaInP visible LEDs	2-18
2.7	History of GaN metal–semiconductor emitters	2-19
2.8	History of GaInN p-n junction LEDs	2-22
	References	2-27
3	History of white light-emitting diodes	3-1
3.1	The advent of the white LEDs	3-1
3.2	Transition from LEDs to LED-based lighting	3-9
3.3	LEDs entering new fields of applications	3-15
3.4	LED replacement light bulbs	3-18
	References	3-19
4	Radiative and non-radiative recombination	4-1
4.1	Radiative electron–hole recombination	4-1
4.2	Radiative recombination for low-level excitation	4-2
4.3	Radiative recombination for high-level excitation	4-6
4.4	Bimolecular rate equations for quantum well structures	4-7
4.5	Luminescence decay	4-8
4.6	Shockley–Read–Hall non-radiative recombination	4-9
4.7	Auger non-radiative recombination	4-14
4.8	Non-radiative recombination at surfaces	4-17
4.9	Competition between radiative and non-radiative recombination	4-21
4.10	Recombination in direct-gap and indirect-gap semiconductors	4-23
	References	4-25
5	Theory of radiative recombination	5-1
5.1	Quantum mechanical model of recombination	5-1
5.2	The van Roosbroeck–Shockley model	5-3
5.3	Temperature and doping dependence of recombination	5-7
5.4	The Einstein model	5-10
	References	5-11

6	Recombination modeled by the <i>ABCCD</i>-model	6-1
6.1	Relation between optical and electrical carrier generation	6-1
6.2	Free carrier concentrations in the active region	6-1
6.3	Recombination expressed in terms of the <i>A</i> , <i>B</i> , and <i>C</i> coefficients and <i>f(n)</i> term	6-2
6.4	Determination of the <i>A</i> , <i>B</i> , and <i>C</i> coefficients in absence of carrier leakage	6-7
6.5	Carrier leakage and the <i>ABCCD</i> model	6-11
	References	6-13
7	Current–voltage characteristics	7-1
7.1	Diode current–voltage characteristic based on Shockley equation	7-1
7.2	Diode forward voltage	7-6
7.3	Diode ideality factor	7-9
7.4	Diode parasitic resistances	7-11
7.5	Measurement of diode parasitic resistances	7-12
7.6	Diagnosis of potential problems in the current-voltage characteristic	7-13
7.7	Ohmic contacts	7-17
7.8	Physics of ohmic contacts	7-19
7.9	Multilayer ohmic contacts	7-22
	References	7-23
8	Carrier transport effects in the active region	8-1
8.1	Carrier distribution in p-n homojunctions	8-1
8.2	Carrier distribution in p-n heterojunctions	8-2
8.3	Effect of heterojunctions on device resistance	8-3
8.4	Carrier loss in double heterostructures	8-7
8.5	Carrier overflow in double heterostructures	8-10
8.6	Electron-blocking layers	8-14
8.7	Effect of heterojunctions on diode voltage	8-15
	References	8-17
9	Design of current flow	9-1
9.1	Current-spreading layer	9-1
9.2	Theory of current spreading	9-7
9.3	Current crowding in LEDs on insulating substrates	9-10
9.4	Buried contact design	9-15
9.5	Lateral injection schemes	9-16
9.6	Current-blocking layers	9-17
9.7	Surface-leakage current	9-19
	References	9-20
10	Alternating-current (AC) and high-voltage (HV) LEDs	10-1
10.1	Simple circuits for AC-driven LEDs	10-1
10.2	LED bridge rectifier configurations for AC-driven LEDs	10-3
10.3	Analysis of pulsed drive current in AC-driven LEDs	10-4
10.4	Challenges associated with AC-driven LEDs	10-6
10.5	High-voltage (HV) LEDs	10-7
	References	10-10

11	Basic optical properties	11-1
11.1	Emission spectrum	11-1
11.2	The light escape cone	11-4
11.3	Emission pattern	11-7
11.4	The lambertian emission pattern	11-8
11.5	Encapsulants	11-11
11.6	Temperature dependence of emission intensity	11-12
	References	11-14
12	Reflectors	12-1
12.1	Metallic reflectors, reflective contacts, and transparent contacts	12-1
12.2	Total internal reflectors	12-6
12.3	Distributed Bragg reflectors	12-8
12.4	Omnidirectional reflectors	12-19
12.5	Specular, diffuse, and mixed reflectors	12-23
	References	12-28
13	Definition of Efficiencies	13-1
13.1	Radiative efficiency (RE) of active region	13-1
13.2	Injection efficiency (IE) of carriers into active region	13-4
13.3	Internal quantum efficiency (IQE)	13-5
13.4	Light-extraction efficiency (LEE)	13-6
13.5	External quantum efficiency (EQE)	13-7
13.6	Forward-voltage efficiency (Electrical efficiency)	13-7
13.7	Power efficiency	13-8
13.8	Luminous efficacy of radiation (LER)	13-9
13.9	Luminous efficacy of a source (LES)	13-11
13.10	Efficiency of wavelength-converter materials (phosphors)	13-11
	References	13-13
14	Designs for high internal quantum efficiency	14-1
14.1	Double heterostructures	14-1
14.2	Doping of active region	14-4
14.3	p-n junction displacement	14-6
14.4	Doping of the confinement regions	14-8
14.5	Non-radiative recombination	14-11
14.6	Lattice matching	14-12
	References	14-15
15	Designs for high light-extraction efficiency	15-1
15.1	Absorption of below-bandgap light in semiconductors	15-1
15.2	Double heterostructures	15-5
15.3	Shaping of LED dies	15-6
15.4	Textured semiconductor surfaces	15-10
15.5	GaN thin-film LEDs	15-12
15.6	Cross-shaped contacts and other contact geometries	15-15
15.7	Transparent substrate technology	15-15
15.8	Anti-reflection optical coatings	15-18
	References	15-19

16	Spontaneous emission from resonant cavities	16-1
16.1	Modification of spontaneous emission	16-1
16.2	Fabry–Perot resonators	16-3
16.3	Optical mode density in a one-dimensional resonator	16-7
16.4	Spectral emission enhancement	16-12
16.5	Integrated emission enhancement	16-14
16.6	Experimental emission enhancement and angular dependence	16-15
	References	16-18
17	Resonant-cavity light-emitting diodes	17-1
17.1	Introduction and history	17-1
17.2	RCLED design rules	17-3
17.3	GaInAs/GaAs RCLEDs emitting at 930 nm	17-6
17.4	AlGaInP/GaAs RCLEDs emitting at 650 nm	17-11
17.5	Newer developments in RCLED devices	17-14
	References	17-15
18	Photonic crystal light-emitting diodes	18-1
18.1	The photon recycling concept for LEDs	18-1
18.2	Thresholdless laser or single-mode LED	18-3
18.3	Photonic crystals	18-5
18.4	LEDs using photonic crystals	18-10
	References	18-12
19	Visible-spectrum LEDs	19-1
19.1	The GaAsP, GaP, GaAsP:N, and GaP:N material systems	19-1
19.2	The AlGaAs/GaAs material system	19-6
19.3	The AlGaInP/GaAs material system	19-9
19.4	The GaInN material system	19-11
19.5	Optical characteristics of high-brightness LEDs	19-13
19.6	Electrical characteristics of high-brightness LEDs	19-15
19.7	Wavelength dependence of the efficiency in the visible spectrum	19-16
	References	19-18
20	The AlGaInN material system	20-1
20.1	The AlGaInN bandgap	20-1
20.2	Crystal structure of III–V nitrides and origin of polarization	20-2
20.3	Consequences of polarization effects in III–V nitrides	20-7
20.4	P-type doping in III–V nitrides	20-9
20.5	Epitaxial growth of GaN on sapphire	20-13
20.6	Dislocations in III–V nitrides	20-15
	References	20-19

21	Ultraviolet light emitters	21-1
21.1	The ultraviolet (UV) spectral range	21-1
21.2	UV and violet LEDs emitting at wavelengths longer than 360 nm	21-2
21.3	UV devices emitting at wavelengths shorter than 360 nm	21-4
21.4	Alternative approaches for UV emitters	21-8
	References	21-9
22	The efficiency droop	22-1
22.1	Introduction to the efficiency droop	22-1
22.2	The “ABC” model	22-3
22.3	The “ABC + $f(n)$ ” model	22-3
22.4	The function $f(n)$ for drift-induced leakage	22-4
22.5	Role of “polarization charges and associated electric fields”	22-9
22.6	Role of “thermal roll-over”	22-10
22.7	Role of “carrier de-localization”	22-11
22.8	Role of Auger recombination	22-12
22.9	Strategies to overcome the efficiency droop	22-14
	References	22-18
23	Human eye sensitivity and photometric quantities	23-1
23.1	Light receptors of the human eye	23-1
23.2	Basic radiometric and photometric units	23-3
23.3	Eye sensitivity function	23-6
23.4	Luminous efficacy	23-10
23.5	Surface brightness	23-12
23.6	Circadian rhythm and circadian sensitivity	23-13
	References	23-14
24	Colorimetry	24-1
24.1	Colors of near-monochromatic emitters	24-2
24.2	Color-matching functions and chromaticity diagram	24-2
24.3	Color purity	24-10
24.4	LEDs in the chromaticity diagram	24-12
24.5	Relationship between chromaticity and color	24-13
24.6	The CIE <i>Lab</i> color space	24-14
24.7	The CIE <i>UVW</i> and CIE <i>Luv</i> color spaces	24-16
	References	24-17
25	Black-body radiation and color temperature	25-1
25.1	Incandescence (heat glow)	25-1
25.2	The planckian spectrum	25-2
25.3	The solar spectrum	25-3
25.4	Planckian radiation in the chromaticity diagram	25-5
25.5	Color temperature and correlated color temperature	25-7
25.6	Standardization of white light by means of color-temperature binning	25-10
	References	25-12

26	Color mixing	26-1
26.1	Subtractive color mixing	26-1
26.2	Additive color mixing	26-1
26.3	Calculation of color mixing	26-2
26.4	Implementation of color mixing	26-5
	References	26-9
27	Color rendering	27-1
27.1	Color rendering of physical objects	27-1
27.2	CIE uniform color space	27-7
27.3	Color-rendering index for planckian-locus illumination sources	27-9
27.4	Color-rendering index for non-planckian-locus illumination sources	27-10
27.5	Criticism of the CRI and alternative approaches	27-13
	References	27-15
28	White-light sources based on LED chips	28-1
28.1	Generation of white light with LED chips	28-1
28.2	Generation of white light by dichromatic sources	28-3
28.3	Generation of white light by trichromatic sources	28-7
28.4	Temperature dependence of trichromatic LED-based white-light source	28-11
28.5	Generation of white light by tetrachromatic and pentachromatic sources	28-14
	References	28-14
29	Phosphors	29-1
29.1	Introduction to phosphors	29-1
29.2	Types of phosphor materials	29-6
29.3	Phosphors used with LED chips	29-9
29.4	Phosphor body color	29-14
29.5	Phosphor structure and synthesis	29-15
29.6	Quenching by temperature and activator concentration	29-19
29.7	Phosphor particle size	29-22
29.8	Phosphor deposition	29-26
29.9	Phosphor sedimentation	29-29
29.10	Quantum-splitting phosphors	29-30
29.11	Location of phosphors in the CIE chromaticity diagram	29-30
	References	29-31
30	White LEDs based on phosphors	30-1
30.1	Efficiency of wavelength-converter materials	30-2
30.2	Wavelength-converter materials	30-4
30.3	White LEDs based on YAG:Ce phosphor	30-6
30.4	White LEDs based on phosphor blends	30-8
30.5	White LEDs using two LED chips and one phosphor	30-10
30.6	White LEDs using violet excitation sources	30-11
30.7	White LEDs using UV excitation sources	30-13
30.8	White LEDs based on semiconductor converters (PRS-LED)	30-15
30.9	White LEDs based on other methods	30-17
30.10	Spatial phosphor distributions	30-18
	References	30-20

31	Packaging: Types of packages for LEDs	31-1
31.1	The 3 mm and 5 mm round LED package	31-2
31.2	The SMD LED injection molded package	31-3
31.3	The SMD LED package fabricated by using a resin-molded body	31-5
31.4	Ceramic-base LED package	31-7
31.5	The side-view LED package	31-9
31.6	Other examples of LED packages	31-11
31.7	Chip-on-board LED packages (COBs)	31-13
31.8	Chip-scale LED packages (CSPs)	31-13
	References	31-14
32	Packaging: Materials used in packaging	32-1
32.1	Resin materials	32-1
32.2	Types of resins	32-2
32.3	Modification of resins by fillers	32-5
32.4	Epoxy resins	32-7
32.5	Silicone resins	32-10
32.6	Advanced resin structures	32-14
32.7	Degradation of resins under harsh operating conditions	32-15
	References	32-16
33	Packaging: Protection against electrostatic discharge (ESD)	33-1
33.1	The human body model and the IEC 61000-4-2 standard	33-1
33.2	The electrostatic discharge process	33-2
33.3	ESD-protection circuits	33-3
33.4	ESD-protection circuits integrated with the LED	33-6
	References	33-6
34	Packaging: Junction and carrier temperatures	34-1
34.1	Carrier temperature and high-energy slope of spectrum	34-1
34.2	Junction temperature and peak emission wavelength	34-3
34.3	Theory of temperature dependence of diode forward voltage	34-5
34.4	Measurement of junction temperature using forward voltage	34-8
34.5	Thermal considerations for pulsed measurements	34-11
34.6	Constant-current and constant-voltage DC drive circuits	34-13
	References	34-15
35	Communication: Optical communication	35-1
35.1	Types of optical fibers	35-1
35.2	Attenuation in silica and plastic optical fibers	35-3
35.3	Modal dispersion in fibers	35-5
35.4	Material dispersion in fibers	35-6
35.5	Numerical aperture of fibers	35-9
35.6	Coupling with lenses	35-11
35.7	Free-space optical communication	35-14
	References	35-16

36	Communication: Communication LEDs	36-1
36.1	LEDs for free-space communication	36-1
36.2	LEDs for fiber-optic communication	36-1
36.3	Surface-emitting Burrus-type communication LEDs emitting at 870 nm	36-2
36.4	Surface-emitting communication LEDs emitting at 1300 nm	36-3
36.5	Communication LEDs emitting at 650 nm	36-5
36.6	Edge-emitting superluminescent diodes (SLDs)	36-7
	References	36-11
37	Communication: LED modulation characteristics	37-1
37.1	Rise and fall times, 3-dB frequency, and bandwidth in linear circuit theory	37-1
37.2	Rise and fall time in the limit of large diode capacitance	37-4
37.3	Rise and fall time in the limit of small diode capacitance	37-5
37.4	Voltage dependence of the rise and fall times	37-6
37.5	Carrier sweep-out of the active region	37-7
37.6	Current shaping	37-8
37.7	3-dB frequency	37-10
37.8	Eye diagram	37-10
37.9	Carrier lifetime and 3-dB frequency	37-11
	References	37-12
	Appendices	A-1
Appendix 1	Frequently used symbols	A-1
Appendix 2	Physical constants	A-5
Appendix 3	Room temperature properties of III–V arsenides	A-6
Appendix 4	Room temperature properties of III–V nitrides	A-7
Appendix 5	Room temperature properties of III–V phosphides	A-8
Appendix 6	Room temperature properties of Si and Ge	A-9
Appendix 7	Periodic system of elements	A-10
Index		A-11